A Comprehensive Methodology for Assessing the Quality of Solar Photovoltaic Systems

A Project Summary Report

Submitted to:
The Alternative Technology Association and faculty of Worcester Polytechnic Institute
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Executive Summary

This project focuses primarily on analyzing the quality of solar photovoltaic systems. As the Australian solar market continues to grow rapidly, consumers are becoming more reliant on solar photovoltaic systems that have inherent failure mechanisms. For this reason, it is important to develop a quantitative methodology capable of comparing these systems and providing the public with products that will perform reliably, at a high level of efficiency for its expected life.

The Alternative Technology Association (ATA) recognizes the need for widespread implementation of renewable technologies and is aware of the lack of reliability and performance analysis of products currently on the market. This project intended to provide a new, more comprehensive assessment methodology for solar photovoltaic systems, focusing primarily on performance and reliability of products; while also providing a better understanding of factors and metrics affecting system quality for ATA consultations.

Methodology

In order to perform the necessary research, the team completed the following four objectives:

1. Research factors affecting solar PV quality

2. Evaluate metrics indicative of solar PV quality

3. Develop an understanding of consumer priorities

4. Design a more comprehensive multiple-criteria decision-making matrix to compare photovoltaic component quality

To begin, the team researched factors affecting solar photovoltaic system quality and common failure modes of systems. The team conducted interviews with industry leaders including manufacturers, retailers, installers, and researchers to gain a better understanding of the operation of solar photovoltaic systems and what factors an industry leader would utilize to classify a system as "high quality". A coding mechanism was constructed to turn qualitative interview data regarding system quality into quantifiable data backed by industry leaders. Table 1 represents the industry leaders interviewed and their combined years of experience in the solar industry.

Table 1: Interview sample distribution

Industry Leader Category	Interviews Conducted	Total Years of Experience in the Solar Industry
Retailers & Installers	10	160
Researchers / Industry Experts	2	32
Solar Manufacturers	3	39
TOTAL	**15**	**231**

Through the data collected in the interviews, the team became aware of reliability data used by industry leaders to determine system quality. The team made use of various research institutions' data, online databases product data sheets, and independent research to draw conclusions regarding reliability and performance of solar products and metrics which best identify them. A survey was sent out to solar consumers to determine consumer priorities when purchasing a solar photovoltaic system. This survey also provided a section for solar photovoltaic system owners to provide feedback regarding their system, any failures it may have had, and data such as panel orientation, inverter type, and panel type. The survey received 868 responses from consumers across Australia. Figure 1 displays the distribution of survey responses across Australia in comparison to the population distribution.

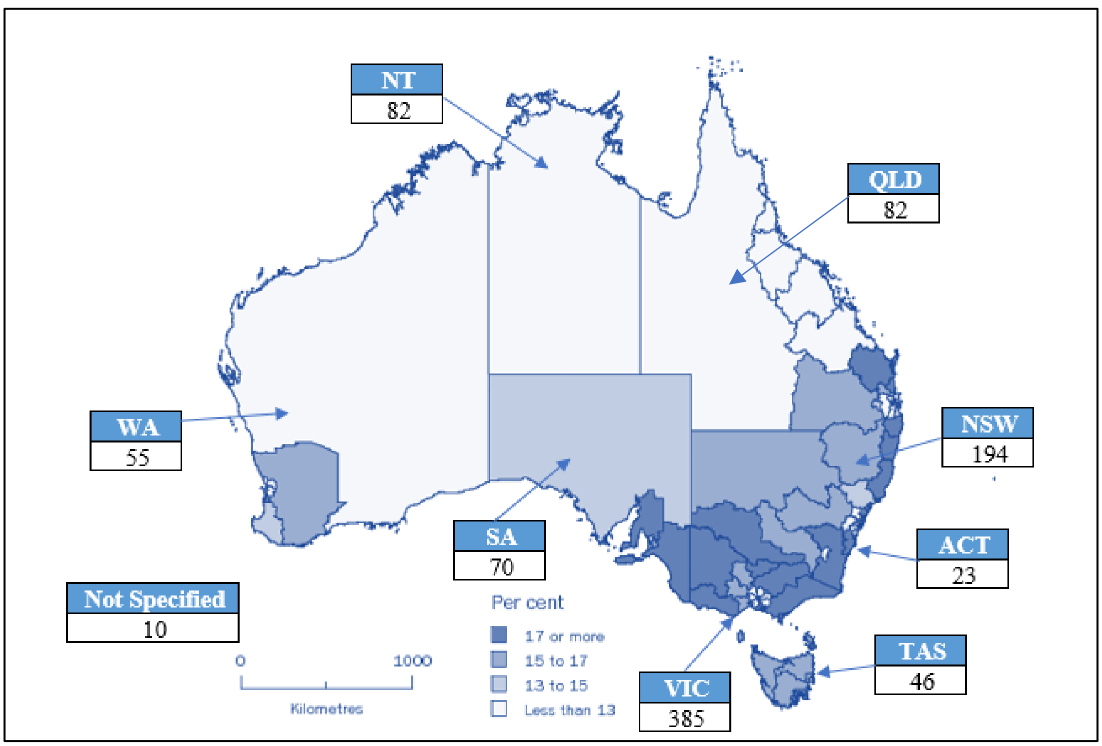

Figure 1: Survey distribution by region

Findings

Consumers recognize the importance of purchasing high quality solar PV systems

Based on the results of the ATA subscriber survey, 70.62% of respondents value the quality of their system over other factors such as price, warranty, customer service, and company experience. This is critical because it mirrors the current need for a more comprehensive quality assessment methodology for solar PV systems. This provides both context and importance to the project detailed within this report.

Importance of various factors affecting the quality of solar photovoltaic systems

Factors such as company reputation and location, system design, and installation were determined to affect the quality of PV systems. Interviewees continually mentioned the reputation and location of a company as important factors to consider when purchasing PV systems. A company with a good reputation and local office has proven the quality of their products and is capable of providing proper after-purchase support. In addition, it is crucial to properly design the system for a given application. The various construction types of solar PV components perform differently from application to application, and failure to account for this during design can affect the long-term reliability and cost of the system. Lastly, selecting a Clean Energy Council (CEC) accredited installer is critical to the performance and reliability of the system. Improper installation can lead to microfractures, water damage, and short circuits that limit the effectiveness of the system.

The Australian energy market currently lacks standardized shipping guidelines

Microfractures are a common failure mode identified by this study that can be mitigated by proper shipping and installation. Microfractures are caused by increased stress on the module glass. This can be caused by loading the glass above its rating. The Australian market currently makes use of CEC installation guidelines, but lacks a similar system for the shipment of PV systems. This creates major uncertainty for consumers when purchasing these systems.

Importance and lack of metrics quantifying the overall quality solar photovoltaic systems

Through research it was identified that the solar PV industry lacks metrics indicative of system quality. Manufacturers are extremely hesitant to publish failure information regarding their products, third party test results are not always unbiased or comprehensive, and products are changing so rapidly that performing reliability tests is extremely difficult. However, use of information of this nature has the potential to provide justifiable, uniform comparisons of PV system quality. For this reason, the team developed a methodology for performing a reliability analysis capable of generating this quantifiable data.

Recommendations

We recommend that consumers only hire installers that are accredited by the Clean Energy Council.

This study identified installation as one of the most common causes for failure with solar photovoltaic systems. Therefore to improve the reliability and performance of PV systems, it is critical that they are installed correctly. In an effort to mitigate the risk of these improper installations, we suggest consumers only make use of CEC accredited solar installers. A company that maintains CEC accreditation has been successfully installing products for an extended time period.

We recommend that consumers solicit post-installation inspections of their systems to ensure the quality of shipping and installation and perform regular maintenance on their systems.

Consumers can solicit these inspections from their CEC accredited installer or from their state government. By conducting these inspections consumers will be able to determine the quality of the installation work. Using Maximum Power Point Tracking will allow the inspector to determine the initial functionality of the system compared to its manufacturer rating. This comparison makes it possible to identify any defects in installation, and correct them before they become more serious post-warranty problems. These inspections should be performed regularly following installation to ensure optimal system functionality. We also recommend that consumers keep a log of all inspections and maintenance done on the system to make potential warranty claims simpler when issues do arise.

We recommend that the ATA work in conjunction with the Clean Energy Council to develop industry guidelines regarding the shipping of solar PV system components.

There are currently Australian regulations regarding both the manufacturing and installation of solar PV components, but there are no such regulations for shipping. Through our interviews and research it was identified that microfractures and other damages are often caused by poor shipping methods such as stacking panels or insufficient protective packaging. This is often because the shipping protocols are currently established by the manufacturers themselves. For this reason, we recommend that the ATA work with the Clean Energy Council to develop a set of guidelines for the proper transport solar PV components, especially solar modules.

We recommend that the ATA solicit failure rate data from solar PV manufacturers.

We recommend that the ATA request manufacturer failure data. Whether this data be from accelerated life testing or warranty claims, this data will increase the amount of reliability data available to the ATA and enhance the certainty to which they can make their assessments. The team was only successful in soliciting failure rate information from one solar manufacturer. If the ATA use their leverage to request this data it will greatly enhance their assessments. This failure data could also be included in their published buyer's guides for personal use by their subscribers, assuming the ATA does not need to sign a Nondisclosure Agreement to acquire the data.

We recommend a project be completed analyzing the quality of off-grid system components and expanding the ATA's assessment methodology for these systems.

The current ATA assessment methodology is primarily focused on the evaluation of grid-connected photovoltaic systems. However, as the Australian energy market continues to change many consumers are making the switch to off-grid and hybrid systems. These systems require additional technology such as batteries and charge controllers. As these two system types become prevalent within the Australian market it will be crucial for the ATA to have the capacity to provide justifiable recommendations to its members regarding these technologies.

Deliverables

Equipped with survey results representative of the Australian population and consumer perspectives, as well as factors and metrics to assess system quality provided by industry leaders and additional research, the team was able to create an enhanced assessment methodology for the quality of solar photovoltaic systems. Each category was reweighted based upon consumer priorities derived from the survey. The quality section included more quantifiable metrics of performance and reliability, allowing for a more accurate analysis of system quality. An application specific tab was also created for the purpose of reallocating weightings based upon the application of the system being assessed. With these modifications, the ATA will be able to provide more comprehensive assessments of solar photovoltaic systems and have more confidence in the data used for consultations.

Other physical deliverables include a registry of both solar modules and solar inverters relevant to the Australian market, a new tender request form for the ATA to easily gather data for their assessment matrix when providing a consultation, and a survey for their website that consumers can access to report system failures. In addition to these deliverables, the team also provided the ATA with research regarding material performance, common failures and how to mitigate them, a comparison of the main categories of solar modules and inverters available on the market today, and a potential reliability analysis for solar PV products using survey responses.

Table of Contents

1. Introduction

The primary objective of this project is to provide the ATA with an improved assessment methodology that more comprehensively evaluates the overall quality of solar PV systems. The final deliverables include a product quality registry and an enhanced quality assessment matrix. This was accomplished by completing the following objectives. The team analyzed the current state of the Australian solar industry to provide a clearer perspective on the requirements of the methodology. Following this it was necessary to investigate the most practical methods for assessing module and inverter quality, and to triangulate the data gathered to provide the most comprehensive quality assessment possible. The necessary data was obtained through interviews and surveys given to primary stakeholders, manufacturer specifications, third-party test data, and assistance from the ATA. By compiling this data and expanding research the project will provide the ATA with the desired deliverables and recommendations to improve their current quality assessment methodology.

2. Methodology

This project is intended to assist the Alternative Technology Association by providing an enhanced assessment methodology for solar photovoltaic systems, emphasizing development of a quantifiable evaluation of reliability and performance. This project offers a more comprehensive recommendation to consumers interested in purchasing solar photovoltaic systems. In order to accomplish our mission, we have four primary objectives:

1. Research factors affecting solar PV quality

2. Evaluate metrics indicative of solar PV quality

3. Develop an understanding of consumer priorities

4. Design a more comprehensive multiple-criteria decision-making matrix to compare photovoltaic component quality

3. Findings & Analysis

This chapter presents the alternatives for better assessing the performance and reliability of these systems. This data was compiled by utilizing available test data from various solar PV test agencies, interviews with solar industry leaders, conversations with key ATA employees, and survey data gathered from ATA subscribers. The combination of these findings resulted in in a more comprehensive decision-making matrix for assessing the quality of bulk-buy tenders and supplementary module and inverter product registries.

3.1 Factors Affecting Solar PV Quality in Australia

It has been established that there are countless factors that alter the life time quality of solar PV systems. This study has identified the most pertinent factors, and we have presented them within this section. This section analyzes various factors that are important to consider that help optimize cost and quality when attempting to purchase solar photovoltaic systems. Considerations include construction of modules and inverters, mitigating common failure modes, company reputation, and office location.

3.1.1 Comparison of Solar Modules

The study has identified the importance of properly selecting the correct construction of solar modules for each specific application. The following section will provide a comprehensive analysis of the differences and benefits of three most common module construction types: polycrystalline silicon, monocrystalline silicon, and thin film solar modules.

Monocrystalline silicon solar modules are commonly the most efficient solar modules on the solar market with an efficiency of roughly 15 to 20% (ENF Solar, 2017). This efficiency is due to the lack of grain boundaries within the cells. Grain boundaries are crystal structure defects that decrease electrical and thermal conductivity of the cells (Mohanty, 2016). However, these high purity and high efficiency silicon solar modules come at a cost. Monocrystalline solar modules are about 10 to 20 cents AUD more per watt than polycrystalline solar modules. On a 5 kW system, this results in a cost difference of 500 to 1000 AUD for a slightly higher efficiency. Monocrystalline solar modules perform the best in average climates, making them a good option for a wide variety of applications.

Comparatively, polycrystalline silicon solar modules are slightly less efficient, with an efficiency of roughly 13 to 18% (ENF Solar, 2017). While the efficiency is still high, it is lower than monocrystalline silicon due to the presence of pronounced grain boundaries (Mohanty, 2016). Similar to monocrystalline modules, polycrystalline cells have a temperature coefficient of 0.45% to -0.50% per degree Celsius. This means that as the panels experience increased heat their output begins to decline. Polycrystalline modules are less expensive than monocrystalline modules and have a similar performance rating, but they are not the least expensive module on the market. Polycrystalline solar modules provide the best balance between price and performance, especially in a mild climate.

Thin film solar modules are currently the least utilized technology on the solar market. Previously, the efficiencies of thin film modules were inferior to the silicon crystal technology used in the previously discussed solar module constructions. However, with increased research and development focusing heavily on thin film technologies, efficiencies have increased and the benefits of thin film solar modules have become more apparent, especially for application in Australia.

The most recent thin film modules claim efficiencies of roughly 10 to 15%, which rival some polycrystalline modules. While the efficiencies are still slightly lower than those of silicon crystal composition, they come at a lower cost, creating an argument for thin film modules. Thin film modules are a few cents less per watt than a polycrystalline module, resulting in a 5 kW system cost that is potentially about 150 to 300 AUD cheaper. While cost is an important factor, one performance metric in particular is allowing thin film technology to grow in the solar industry; that metric being the temperature coefficient. The temperature coefficient of thin film modules is significantly lower than that of crystalline modules. Thin film module efficiency decreases about 0.25% per degree Celsius, which is almost half that of its silicon based rival (ENF Solar, 2017). This means that thin film solar modules perform much better in hotter climates, and with a much higher base efficiency than in previous years, the performance of crystalline and thin film can be considered comparable. This makes them especially viable for the hot Australian climate. As research and development of thin film technologies continues, thin film modules may be more beneficial in hotter climates. A 2011 study was conducted on a Copper Indium Gallium Selenide (CIGS) thin film module, achieving record efficiencies of 20.1 and 20.3% in a laboratory environment (Jackson, 2011). While this was only in a laboratory environment, the methods proved reproducible, and as technology increases, eventually we may see thin film technology surpass that of crystalline silicon.

Another added benefit to thin film modules is their appearance. The modules are simply sheets of glass with photosensitive materials thinly layered onto them. This allows for more versatility with installation methods. With the backing consisting solely of glass, thin film modules can have varying opacity ratings. This means that thin film cells can be placed onto roofs as translucent skylights. This provides a more subtle implementation of solar technology that does not affect the overall appearance of a consumer's home. While thin film solar modules are commonly least efficient, they are a developing product that performs better in higher temperatures and introduce a new perspective in solar panel aesthetics.

The large variance between the three solar module construction types creates the need for proper system design when consumers implement systems. By installing the solar modules best suited for the application, consumers increase the life time performance and reliability of their system. Therefore, it is crucial to inform solar consumers of this and account for these differences when the ATA provides consultation.

3.1.2 Comparison of Solar Inverters

There are two major types of inverters that are implemented in residential and commercial photovoltaic systems in Australia. Ideal inverter selection is application dependent, and both string and micro inverters are commonly used. Neither type of inverter is superior to the other, but can be better suited for specific applications. String inverters are often implemented on larger scale systems and when there are price constraints. Micro inverters are much more effective when individual modules are affected by shading or multiple panel orientations are desired. This section will provide a comparison between the advantages and disadvantages of each type of inverter.

String inverters are the conventional solution to power conversion in photovoltaic systems. String inverters typically have a capacity between 1kW and 10kW and service many panels connected together in series or parallel configurations. String inverters support isolated power conversion in a single instrument. This allows for simple installation and convenient access to the inverter as it can be mounted at the ground level and either inside or outside (Energy Matters, 2016b). String inverters are highly efficient as well and typically have longer lifespans than other alternatives. The technology has been around for a long period of time, so the electrical systems have become very robust and affordable.

However, string inverters do have a few limitations. There can be long strings running from solar arrays to the inverter. This can make installation a bit more complicated and introduce increased risk levels. Since many panels are wired together, the direct current can reach very high levels. Wires and electrical components must be rated to carry increased loads within string-connected systems. These high current lines can present safety hazards to installers, maintenance workers, or emergency responders in the event of a fire or other disaster (Peacock, 2015). Additionally, since all of the panels are connected together, individual panels can compromise the entire system. All panels on the same string must receive similar light levels and have the same orientation. If a single module is shaded, for example, then the maximum system current is limited by that panel. This will result in excessive heat dissipation within the shaded cell and can lead to hot spots or other failures. String inverters only perform system level maximum power point tracking and cannot monitor individual panels.

Though, the functionality of string inverters can be greatly improved through the implementation of power optimizers. Optimizers are small devices and are mounted on the backside of each panel. They support panel level maximum power point tracking and data acquisition. The optimizer is a DC to DC converter and increases the amount of power that is delivered to the string inverter (Energy Matters, 2016b). Optimizers also allow panels to be mounted at many different angles and grant increased system customization. These devices are also equipped with additional safety features that automatically turn off current from individual panels when the inverter or grid is powered down. While optimizers increase the cost and complexity of installation, they significantly enhance the capabilities of string connected systems.

Micro inverters have been rapidly expanding their presence on the solar inverter market. The first commercially successful inverters were released by Enphase in 2008, and have since been becoming more and more prevalent. Micro inverters are different from string inverters in that power conversion is completed directly at the individual panels (Energy Matters, 2016b). Micro inverters are mounted to the back of solar modules and alternating current is delivered out of the micro inverter. This allows for each panel to be independent of each other and connected in parallel. Photovoltaic systems with micro inverters can be planned with greater flexibility in design and panel orientation because panels are not interdependent upon each other. Micro inverters support module level maximum power point tracking and thus improve total power output of a solar system. Micro inverters are also outfitted with data acquisition hardware, and panel level performance can be monitored to identify faulty panels. Additionally, there are no high power DC lines which reduces the safety risks associated with photovoltaic systems. Micro inverter manufacturers also commonly offer 25 year limited warranties, which is significantly longer than most string inverters.

One major drawback with micro inverters is the increased cost in comparison to string inverters. Micro inverters are significantly more expensive, but grant enhanced functionality (Peacock, 2015). Even systems outfitted with string inverters and optimizers, which deliver similar benefits, are less expensive than micro inverters. Additionally, micro inverters have not been on the market for very long, and thus the extended lifetime reliability is unknown. Since these inverters are mounted outdoors and on the back of panels which get extremely hot, (in excess of 45 degrees Celcius) the inverters are required to be extremely robust and durable. Furthermore, these inverters employ electrolytic capacitors which are temperature sensitive and have a limited lifetime. While the rest of a photovoltaic system can still function if a micro inverter fails, there are more possible points for a system to experience failure because there are so many inverters. Failed micro inverters are also difficult to replace because they are mounted on roofs and connected to the panels.

Similarly to modules, it is important to identify these differences and how they affect systems within the given application. A high quality system that is improperly designed for the application will experience system failures and increased maintenance costs which reduce the benefits of purchasing the higher quality system. Therefore, correctly selecting the inverter will optimize the power output of the system and lengthen the product's life span, which is financially beneficial to the consumer.

3.1.3 Importance of Module/Inverter Capacity Ratio

One of the major design considerations when implementing a photovoltaic system concerns the sizing ratio between the solar array and inverter. There are many different views about the optimal relationship in capacity between the solar modules and inverters. It is not necessarily best to match a panel array to an inverter rated at the same value. Some believe that it is best to be conservative and oversize the inverter, while others find that the best solution is to undersize the inverter and maximize performance during off-peak hours.

One system configuration is to have an oversized the inverter with buffer capacity over the maximum power output of the modules. This configuration was very common when modules were much more expensive, and installers wanted to maximize power during peak daylight hours. A matched or oversized inverter will never be power limiting, and the inverter will not be responsible for capping performance (Fiorelli, 2013). Additionally, oversizing an inverter and running it below maximum operating conditions will not severely tax or stress the device and potentially extend the life of the inverter. Though, photovoltaic systems will rarely produce their theoretical capacity according to the nameplate nominal power ratings of the modules. Factors such as shading, orientation angle, irradiance quantities, and operational temperature cause panels to only operate at peak efficiency for a minimal period throughout the day (Morris N., 2017). Thus, even a "matched" system will never run the inverter at peak power. The costs associated with purchasing increased inverter capacity also detract from the proposition of oversizing inverters. Many installations today will opt to undersize inverters in order to reduce initial costs and the margin between inverter capacity and actual power generation.

Undersized inverter configurations allow the inverter to run at levels closer to peak capacity for longer periods of time during daylight hours. This ratio between inverter and array may limit, or clip, power during times of peak sunlight, but it also maximizes system efficiency during periods of lower solar irradiance (Morris N., 2017). Figure 2 demonstrates the compromise between clipping and increased energy during off-peak hours. Under sizing inverters both reduces start-up costs and limits operational expenses, as less power is consumed to run smaller inverters. Modern inverters are constructed with the intention of being installed with solar arrays of larger capacity. The inverter manufacturer SMA even states that their products can be used in applications where the module array is 20% larger than the inverter's capacity (Partlin, 2015). Inverters use maximum power point tracking in order to optimize the operating point on the current-voltage curve and deliver the most power. This same principle is used to enable power limiting for the inverter. The operating point on the inverter's current-voltage curve is manipulated to deliver higher voltage and reduced current, yielding reduced power (Fiorelli, 2013). This causes clipping

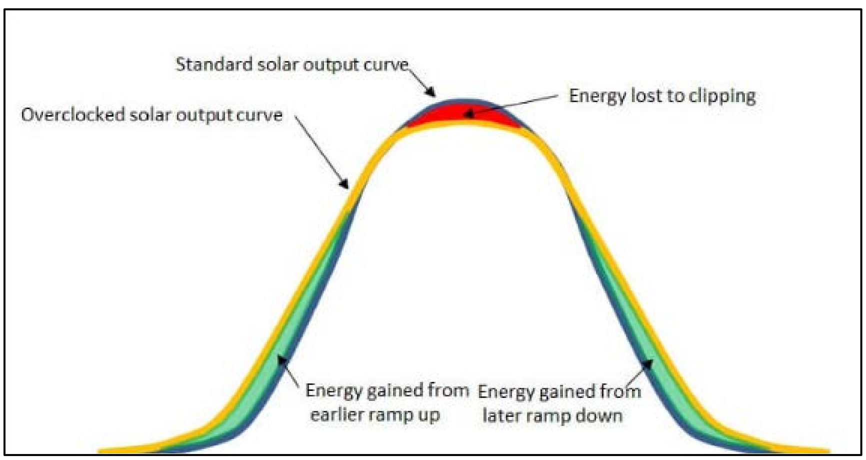

Figure 2: Solar output curve (Morris N., 2017)

and does not allow power to surpass the inverter's rated capacity. Solar inverters are intended to be used in undersized applications, but there are certain limitations that must never be surpassed such as the maximum input power or voltage (Partlin, 2015).

The Clean Energy Council (CEC) publishes guidelines that all Australian solar PV manufacturers, designers, and installers must abide by. In order to limit potential safety hazards, the CEC mandates that inverters must meet at least 75% of the rated capacity of the panel array (NECA, 2013). The CEC also requires that solar array capacity must not exceed any manufacturer specifications for maximum power input to the inverter. These restrictions provide a sufficient margin to allow for oversizing to occur, while assuring that system configurations do not compromise safety.

Utilizing our survey, the team used data given regarding each consumer's system to understand the current status of undersizing and oversizing systems in Australia. As shown in Figure 3, the most common configuration is oversizing the inverter in comparison to the module. 47% of people have an oversized inverter for their system. Following that, having a perfect ratio between the inverter and module is second with 33%. Lastly, undersizing the inverter is the least popular configuration with only 20% of consumers with these conditions. It is important to note that 235 of the 607 people that owned photovoltaic systems in the survey were unsure of the sizing ratio of their system.

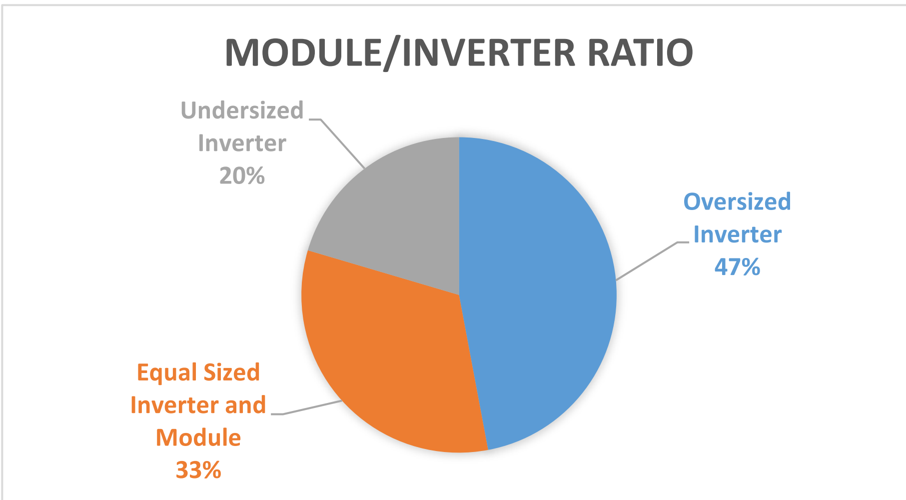

Figure 3: Survey Data Regarding Module/Inverter Ratio

3.1.4 Common Failure Modes

Despite a lifespan of roughly 25 years, modules can fail much earlier. Common problems include open or short circuit failures, module delamination, hot-spot failures, and microfractures (Honsberg, 2017a). Open circuit errors often happen when the bus wires that connect each individual cell are broken, preventing the flow of electric current. Individual cells can also be short circuited, and not generate power as a result of weathering, delamination, or manufacturing defects. Module delamination occurs when the protective coating surrounding all of the cells begins to form bubbles or peel off the module. This is caused by weathering or poor adhesion to the surfaces, shown in Figure 4. Hot spots begin when many cells connected in series receive sunlight, but one or two cells are left in the shade (Honsberg, 2017a). Figure 5 displays a module with a hot spot failure. This will cause high power dissipation and overheating in the shaded cells, and cause hot spot damages. PV manufacturers are aware of these different types of failure modes, and attempt to mitigate the issues. For example, lamination techniques have dramatically improved in recent years, strengthening the entire module and making it more resilient to changes in moisture and temperature levels.

Figure 4: Module Delamination Failure (First Green, 2014)

Figure 5: Module Hot Spot Failure (First Green, 2014)

Figure 6: Microfractures that have expanded over time (Fletcher, 2017)

One of the most common modes of solar module failure is the development of miniscule cracks within solar cells that cannot be seen by the human eye, known as microfractures. Microfractures can have a significant impact on a module's performance. This form of degradation is caused by numerous factors, but can typically be traced to excess stress on the module or manufacturing defects (Köntges, 2011). The excess stress can be caused by environmental factors such as a large thermal variance between day and night, humidity, and high wind speeds which are all pertinent in the Australian case. Due to their miniscule size, microfractures often go unnoticed for up to two years, and slowly degraded the module without the consumer knowing. In addition to environmentally-caused stress, mechanical stress can arise during shipping and installation. Examples of this include improper shipping techniques, installation that allows for module flexure, and dropping of or stepping on panels during installation. No matter the cause of the microfractures, these defects have the capacity to separate cells and render them inactive, causing a decrease in panel output of upwards of 2.5% (GSES, 2015). Microfractures also have the potential to cause the aforementioned hot spots which further reduce panel efficiency. These defects cannot be repaired, and therefore extreme care in manufacturing, installation, and maintenance must be employed to minimize their effects. Figure 6 displays advanced microfractures that have been allowed to expand to a size visible to the human eye.

In an attempt to minimize the presence of microfractures, some manufactures conduct Electroluminescence (EL) tests. EL testing makes use of non-visible light emitted by passing current through solar cells. This light is then detected by a special camera, and any present microfractures are identified. Selecting a manufacturer that conducts these tests is helpful in ensuring the long-term quality of the solar modules. Figure 7 indicates the different types of errors found in solar systems globally, by percentage, accounting for failures in solar modules after being in use for eight years (Köntges, 2014). It is also important to note that only 2% of the modules observed had failed after eight years.

Photovoltaic modules are susceptible to failures, but inverter problems pose a much larger threat to a system's continued operation. A failure modes analysis completed in Italy found that 76% of outages at solar PV plants are caused by inverter failures (Cristaldi, 2014). These failures are often caused by problems with thermal management, heat extraction, or lightning. Lightning commonly causes electrical overloads in inverters if proper precautions such as lightning rods or internal grounding are not implemented. The most sensitive components within inverters are often considered to be the electrolytic

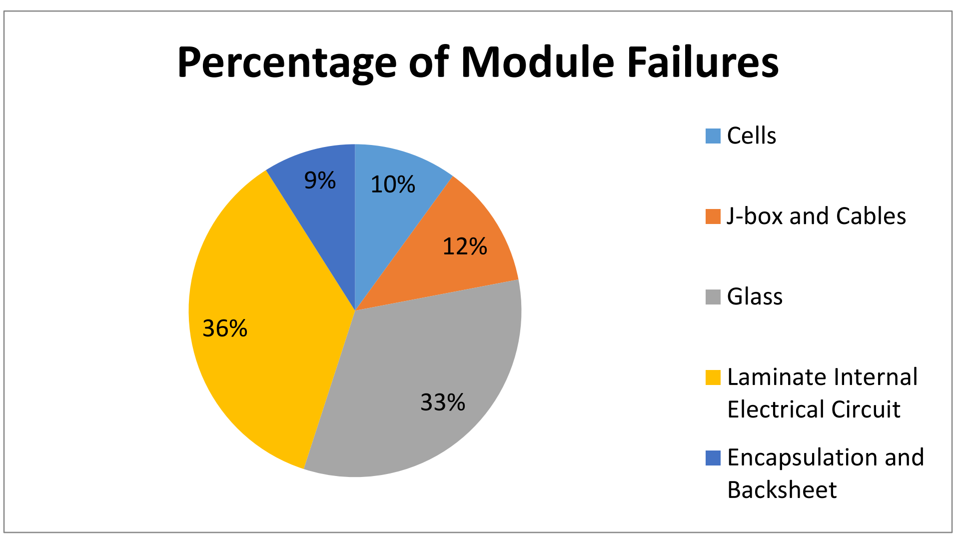

Figure 7: Global failure mode distribution (Köntges, 2014)

capacitors and the insulated gate bipolar transistors (Cristaldi, 2014). These devices are commonly exposed to both thermal and electrical stresses which compromise the inverter's lifespan. Additionally, inverters are commonly plagued with manufacturing flaws that contribute to decreased performance and efficiency.

While manufacturing issues do occur, most issues are caused by inadequate installation. Improper installation can result in electrocution, leaky roofs, broken glass from thermal stresses, overheating at the inverter, loss of warranty, and a variety of other concerns. Installers in Australia must be especially attentive to mounting solar panels due to its climate. High temperatures reduce the efficiency of photovoltaic cells and increase the risk of fires. In some parts of Australia, particularly Western and Northern parts of the country, cyclones are a major threat, and PV systems must be installed to withstand excessive wind speeds.

3.1.6 Mitigating Common Failure Modes

Through interviews with industry leaders and manufacturers, this study identified additional failure modes in solar photovoltaic systems common within the Australian case. By coding these interviews in accordance with the mechanism shown in Appendix H the data presented in Figure 8 was compiled. This section will address the most common responses from these interviews and how to mitigate their effects. In turn, reducing the occurrence of these failure modes will improve the overall performance and reliability of a consumer's solar PV system. As seen in Figure 8 this study found that there are five primary failure modes of solar photovoltaic systems: DC isolators, installation error, inverter

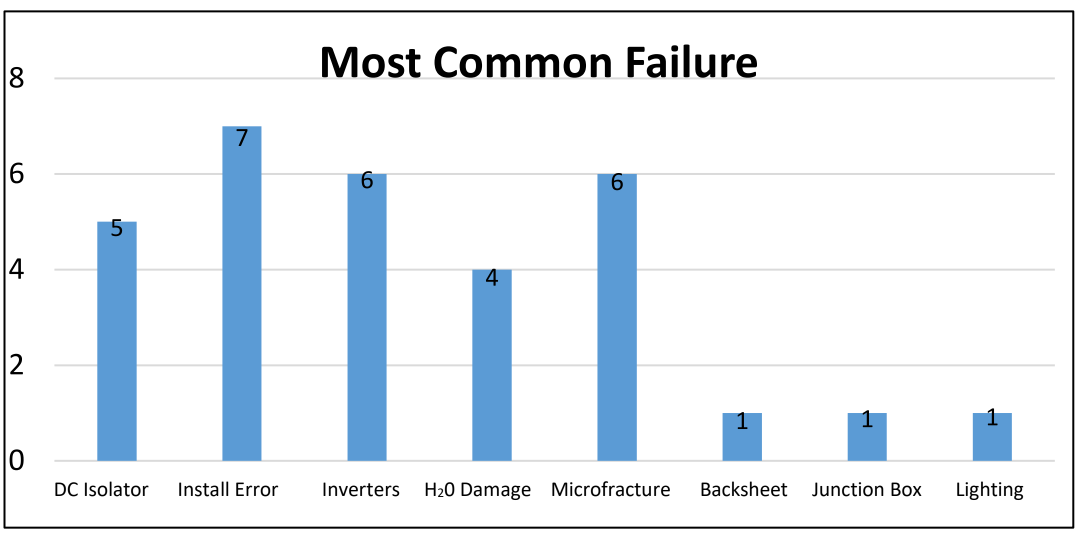

Figure 8: Distribution of most common failure

failure, water damage, and microfractures. Each of these issues will be addressed within this section.

One of these primary failure modes in Australia, identified by this study, is the formation of microfractures within solar modules. These failures are caused by environmental events, manufacturing errors, and poor shipping or installation practices. As a result, systems experience significantly reduced output (GSES, 2015). The Australian climate is subject to high wind speeds (cyclones) and humidity levels which have the ability to cause these microfractures. However, it is extremely difficult to control the environment's impact on the formation of microfractures, which makes it critical to purchase a high quality system manufactured with durable materials. High tempered glass is the most durable glass option for solar modules, and should be used to mitigate the effects of impacts caused by the environment.

It is far easier to mitigate the occurrence of human error than the environment. These human errors are present in the manufacturing, shipping, and installation of solar modules. Fractures can occur at any point throughout the manufacturing process due to a wide variety of errors. For this reason it is crucial to purchase panels from a manufacturer that conducts Electroluminescence testing to check for these cracks. Consumers can be assured that panels that pass this testing are free of microfractures leaving the factory. Although, EL testing is not required in the Australian market, subjecting modules to this testing not only mitigates microfractures, but can be seen as an indicator of good quality. When purchasing panels, consumers should insure that the product they are purchasing has been EL tested.

However, the majority of microfractures occur in the shipping and installation process. There are currently no industry standards for regulating the shipping of these products, and specification for proper delivery is left to the individual manufacturers. This leads to a large variation in the quality of transportation methods, creating a problem because modules are so susceptible to microfracture degradation. Throughout the shipping process panels can be subject to harmful vibrations due to the delivery vehicle, excess loading caused by stacking panels above their weight rating to increase, and insufficient packaging. All of these factors are capable of causing microfractures that decrease the long-term quality of the panel before it can be installed. Thus, this study has identified the need for a standardized shipping process that helps to mitigate microfracture due to shipping.

In addition to improving delivery methods, improving solar installation techniques will help reduce microfracture formation. There are three primary installation causes of microfractures: dropping of the panel, stepping on the cells, and installation on a nonplanar surface. These can cause the panel to distort in ways that it was not intended, causing microfractures in the cells to form. In order to mitigate these installation errors, solar consumers should only make use of Clean Energy Council Accredited

Installers. These companies use installation practices that meet Australian industry requirements, and provide consumers with the highest likelihood of proper installation.

Microfractures can still occur even after the panels are delivered and installed. For this reason it is important for solar owners to inspect their systems twice annually (GSES, 2015) and perform the necessary maintenance required of the system, such as cleaning and removal of debris from the modules. Panel-level monitoring (provided by either micro inverters or optimizers) allows consumers to view the current output of individual panels, which can then be used to identify panels that are operating at sub-optimal levels. Maintenance and monitoring are crucial to the sustained prevention of microfractures within systems.

In addition to using higher tempered glass, an accredited installer, and properly maintaining systems this study has identified a design characteristic that has the potential to eliminate the formation of microfractures in solar modules. For many years, solar cells were consistently thicker than 1mm. This made it extremely difficult for microfractures to form, but as technology advanced, manufacturers reduced cell thickness in attempt to save money on materials. In fact, cell thickness has reduced so much that they can currently be as thin as 0.1mm (Morris G., 2017). Cells that are thinner than 1mm lose their structural stability but maintain their rigidity allowing vibrations and impacts to cause these harmful microfractures. It has recently been proven that as these cells are able to become thinner than 0.05mm. At this point the cells become flexible and the risk of microfracture is eliminated (Morris G., 2017). Therefore, in an attempt to minimize the potential risk of microfractures, consumers should be aware that panels ranging from 0.05-1mm have a higher tendency of forming these defects. Adhering to these suggestions will minimize the effects of microfractures and increase the life time output of solar modules.

The inverter is a vital PV component that is widely known to cause system failure. In fact, 51% of consumers that provided failure information claimed that the cause of their system failure was the inverter. Survey results show that water damage, overheating, and damage by impact or wildlife are the leading causes of inverter failures. In order to reduce these failures it is critical to operate the product in a dry, cool, and secure location. Due to their construction, these products will still fail at a much faster rate than modules, and consumers should expect to purchase at least two inverters throughout the life of their modules.

Installation error was discussed briefly earlier in this section, but its effects are for more broad than solely microfractures. The data in Figure 15 suggests that installation error is the most common cause of failure within PV systems. Improper installation can lead to decreased efficiency, loss of power generation, and potential system fires. Analysis of consumer data gathered from the study's survey shows that 23% of consumers who experienced a system failure attribute it to incorrect installation. As previously stated, hiring a CEC accredited solar installer will reduce the risk of an installation failure. In addition, consumers should be informed of the installation company's experience in years and number of installations. These values are utilized in the current assessment matrix, and when used in conjunction with a CEC accreditation will improve the overall quality of solar PV installations.

Lastly, the interviews identified water damage to both the inverter and modules as a major problem with solar photovoltaic systems. Introducing water to the electronics within both the modules and inverters causes short circuits and reduced output. Properly sealing the modules during installation and choosing products that have high quality backsheets will make it difficult for water to reach the electronics. Sealing the modules is performed by installation professionals, and can be mitigated using the same methodology discussed for installation earlier in this section. Polyvinyl fluoride is the most commonly used backsheet material and is sufficiently water resistant. Consumers should be sure the system they are purchasing makes use of this material or a similar polymer.

3.1.7 Company Reputation and Location

Based upon the team's interviews with solar industry leaders, there is a trend within the solar industry to determine a product's quality based on the reputation and location of the product manufacturer. Similar to the ATA, the majority of solar suppliers and installers determine a product's quality using previous experience with a manufacturer and customer review forums. This method of assessing solar system quality makes it difficult to draw comparisons and allows for bias to alter results. While these companies do have access to limited reliability and performance data, they do not make use of them due to the speed at which manufacturers produce newer technologies and difficulty in obtaining pertinent data.

Figure 9 displays the distribution of metrics utilized to determine solar photovoltaic system quality. This information was gathered by implementing the coding mechanism found in Appendix H for interviews with 15 Australian solar industry leaders. Reputation was the most overwhelming interview response. This study found that most experts were concerned with the existence of companies created to make a quick profit rather than long-term success. Numerous interviewees felt that consumers should only utilize companies (both manufacturers and installers) that have been in the market for an extended period of time and have positive reviews from past customers. With limited quality data accessible to the public, company reputation is a good way to estimate the eventual quality of a product or installation.

In addition to company reputation, many experts felt that company location also played a vital role in the quality of solar PV systems. While it was found that the majority of products were manufactured in Asian countries, using similar materials, experts felt that having at least one Australian office or branch helped to ensure the long-term quality of systems. One interviewee stated, "Having an Australian office shows a commitment to the market and to providing quality products to their customers" (Morris G., 2017). Having an Australian presence allows companies to provide maintenance and advice quickly, honor warranties, and become more knowledgeable of the Australian solar landscape. This is

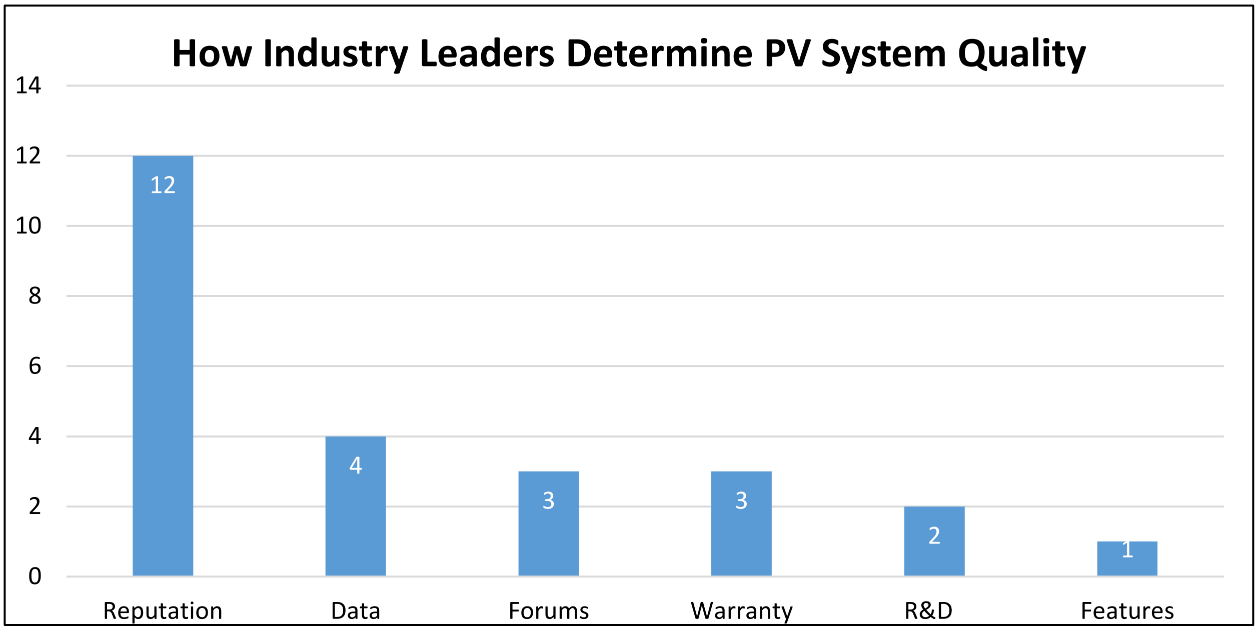

Figure 9: Interview results of how experts assess quality

important because assuring the life time quality of a system is a primary contributor to the financial benefits of solar photovoltaic systems. These companies have the resources necessary to establish international markets, which indicates corporate stability and success. Solar PV consumers should make note of the nearest location of both their manufacturer and installer when purchasing systems. This should provide peace of mind and ease of future quality assurance.

3.2 Metrics Indicative of Solar PV Quality

The following section was compiled through investigation of available third party test data, product data sheets, and independent research. Similarly to Section 4.1, this section will address the analysis of PV system quality. However, this section consists of data metrics that can be utilized to provide quantifiable analysis and comparisons of products. The metrics evaluated in this section include: certification testing, performance ratio, and PTC data. This section also includes a potential methodology for creating future reliability data.

3.2.1 ENF Solar Online Database

Through the team's research, the ENF Solar Database was discovered. This represents a free database that is continuously updated and provides relevant data regarding all major components of solar PV systems. It utilizes its contacts and employees to identify any new solar products or companies entering the industry and will remove any system components that are no longer available for sale anywhere in the world. The database contains pertinent information for 28,020 solar panels, 8,675 inverters, 1,399 mounting systems, 98 EVA encapsulant varieties, and 213 back sheets. These product pages list information found on datasheets as well as performance data, material composition, any lab testing or ranking done on the product, and consumer reviews. There is also an option to compare two products side by side, displaying all the information for both products in a comparable format. In addition to manufactured products, the ENF keeps a running list of all solar installers. They have a list of 22,780 solar installers to date. These installers can be separated by region. For example, there are 1,485 solar installer companies in Australia. Each company contains information such as important contacts, location, what panels and inverters they provide (and links to those products), and any reviews on the company they could find. The ENF website is constantly updating and easily navigable, making it very useful for maintaining ATA product data.

3.2.2 Certification Testing

Solar photovoltaic systems must meet standardized codes in order to be installed in every state within Australia. Photovoltaic systems also have their own specific requirements that must be addressed. Each solar module is required to meet the International Electrotechnical Commission's (IEC) standards for solar panels. According to the Australian regulations, every module must be IEC 61730 certified and either IEC 61215 or IEC 61646 certified (Clean Energy Council, 2014). IEC 61730 certification is attained by meeting multiple construction, material, and manufacturing requirements. This certification provides a baseline level of quality that can be expected from each solar module.

IEC 61730 and IEC 61215 certifications pertain to lifecycle and failure testing for solar modules. IEC 61730 standards exist to test crystalline silicon panels while IEC 61215 standards are in place to evaluate thin-film solar modules. These standards enforce that manufacturers complete failure mode analyses and accelerated lifecycle testing. These tests grant confidence in solar panels because manufactures subject the panels to many different cycling stresses such as thermal, electrical, luminescence, wind, hail, hot spot, and humidity. The team attempted to find test data on accelerated life testing, but no research seems to be published relating to lifecycle testing on a wide range of models of solar panels. Although, this certification provides an indication that the companies have completed this sort of analysis internally on their products, and that modules in the field are up to specification. National Renewable Energy Laboratory believes that IEC 61215 is a main contributor to helping the solar industry attain field failure rates and warranty returns below 0.15% (Wohlgemuth, 2012).

Another type of certification that exists for flat-plate solar photovoltaic modules is the UL 1703 Standard. This is a set of requirements that define engineering design and construction. These manufacturing guidelines outline proper procedure for materials, wiring, fire protection, impact testing, and performance testing. This certification is not required by the Clean Energy Regulator, but is an indication about further attention paid towards system quality. Though, as greater market pressure is placed on companies to deliver more efficient and resilient products, stricter standards and manufacturing processes will continue to be adopted across the industry. Referring to these certifications is important in assessing system quality because failure to obtain these certifications indicates a product is of lower quality.

3.2.3 Utilization of Previous Model Data

Reliability and quality test data allows for a more comprehensive quantitative analysis and comparison of various products. However, it is quite difficult to keep a current list of product data due to its limited availability and the extended period of time needed to test the longevity of systems. Through investigation of a solar quality test agency, Choice, the team identified that data from a previously tested product that is now superseded by a more updated technology can be used to assess the newer product, within reason. The direct quote can be found below:

"Tested models are mostly now superseded by newer, higher-spec versions. Regardless of their score, we don't recommend models that are not currently available for you to buy. But you can still use our test results for them; if a panel performed well in our test, you can reasonably expect a good result from any higher-yielding panel that replaced it." (Choice, 2017)

This helps solve the issue of maintaining the most up-to-date quality test data for products on the market. While the reliability data will not always be completely current, it is reasonable to utilize similar data to draw conclusions and make comparisons between various solar photovoltaic products. In addition to company reputation, discussions with these industry leaders have shown that a manufacturer's presence in Australia is also important in identifying quality. Currently, multiple solar suppliers have stated that having an office/headquarters in Australia shows a commitment to providing quality products capable of handling the Australian environment. While it does show commitment, having an Australian office forces the company to comply with Australian quality manufacturing standards.

3.2.4 Performance Metrics

There are a number of independent organizations that test photovoltaic components in order to better understand performance and confirm nameplate values released by manufacturing companies. The majority of these laboratories are concerned with checking the actual power generated under electroluminescence testing and yield testing. There are two different types of testing that are commonly used to evaluate the initial performance of photovoltaic modules. These tests are either completed under standard test conditions (STC) or photovoltaics for utility scale applications test conditions (PTC). STC testing is completed with ambient and cell temperature both at 25 degrees Celsius. Photon Laboratory and Choice have completed STC power testing on many of the leading solar modules on the market. PTC testing is completed under conditions that solar modules are more likely to experience under normal operation. The ambient testing temperature is set to 20 degrees Celsius, cell temperature is brought to 40 degrees Celsius, and a cooling air speed is blown across the module at 1 meter per second. PTC power measurements are lower than that of STC because solar modules are less efficient at higher temperatures. Go Solar California has compiled a very large public database of solar modules tested under PTC.

Power yield data is also collected by photovoltaic research laboratories as well. The research facilities often acquire a wide range of commercially available solar modules and measure the amount of energy produced over a long span of time. Climate data such as temperature, wind speed, and global horizontal radiation are also recorded continuously throughout the day. These sorts of measurements allow for yield data to be calculated and compared across many different products. Additionally, using the recorded power and irradiance values, the performance ratio, or quality factor, can be calculated. This allows direct comparison across any model or type of panel because it assesses the amount of power produced in relation to the rated nameplate values. Desert Knowledge Australia Solar Centre (DKASC), Photon Laboratories, and CSIRO each run extended lifecycle tests on solar modules. Photon and CSIRO publish rankings for each of the modules in the tests while DKASC releases the actual data recorded.

3.2.5 Performance and Reliability Metrics Table

Assessment Metric	Characteristic Quantified	Description	Importance
Mean Time to Failure and ISO 9000 Certifications	Reliability	The average time for a PV component to experience its first failure	Manufacturers that are ISO 9000 certified have met industry standards. If the manufacturers are not ISO 9000 certified, it does not necessarily reflect their products as non-quality, but lack of certification represents a company without an established mechanism for assuring the quality of their products (EnergySage, 2016).
Mean Time Between Failures	Reliability	Calculated based upon the average time span between component failures during the useful life stage of a system	This stat is useful in determining how long the equipment will remain functional.
Efficiency	Performance	Percentage of solar radiation the PV system converts to usable energy	It is crucial that solar systems operate at a high level of efficiency in order to produce the maximum profit for investors. Monitoring and recording efficiency data can provide insight into the system's degradation over time, and help to quantify its life-long performance.
Power Tolerance	Performance	The certainty with which the system's power output is rated	A smaller tolerance percentage range means more certainty and is to be viewed in correspondence with solar panel ratings.
Temperature Coefficient	Performance	Quantifies panel efficiency above optimal temperature	Many panels produce 1% less electricity for every 2°C increase after 25°C. Panels with a smaller temperature coefficient perform better in higher temperature regions and are more reliable long term (EnergySage, 2016).
Warranty	Reliability	Manufacturer coverage of electricity output and material operability	Warranties are good metrics for investigating system lifetime quality. Warranties are strong indicators of quality, but they cannot be solely referenced to determine system quality.
Degradation Rate	Reliability & Performance	Declination percentage of electricity output	Many manufacturers guarantee a maximum loss of 20% efficiency over the first 25 years after the installment date (EnergySage, 2016). The majority of solar PV modules have a degradation rate of approximately 0.7% each year (EnergySage, 2016).

3.2.6 Reliability Analysis

In the future, as standards become more enforced and the solar industry continues to grow, reliability data is expected to become more readily available. With reliability data, the ATA can perform calculations to determine the reliability of different solar photovoltaic systems. However, due to a lack of standards set within the industry, as well as company privacy issues, the team was unsuccessful in obtaining manufacturer reliability data, such as time to first failure. There are two methods for determining the reliability of a solar PV system. The first being to make use of time to first failure data and perform a statistical analysis based upon real world failures. The second option entails using failure probabilities and system design to estimate potential reliability prior to a product's implementation. This method does not require time to first failure data to make estimates. This section addresses both of these methods and provides a mechanism for performing accurate, numerical based calculations of system reliability that the ATA can utilize as reliability data becomes more readily available.

While there is a lack of readily available data points, the Alternative Technology Association has the ability to obtain this data in two ways. The first being solicitation of failure test information from manufacturers and installers within their tender request form. Companies must conduct these tests in order to calculate their warranty values, and are unwilling to make these results public without signature of Non-Disclosure Agreement. However, requirement of this information within the tender document could potentially make companies more likely to comply. The second alternative involved the creation of an ATA subscriber failure data base. This data base should include product make and model, time to first failure, and what type of failure occurred. Generation and maintenance of this database would create the necessary data points to calculate a reliability metric capable of comparing the quality of products. The analysis shown within this section makes use of coded failure data gathered from the ATA subscriber survey as an example of the potential for this data base.

The first reliability analysis method makes use of time to first failure to measure reliability. The data from the subscriber survey was gathered and entered into Microsoft Excel to provide failure data for this analysis. By utilizing the software's computational abilities a regression analysis was performed on failure data. Based on the sample of failed products, a linear regression can be done to find the relationship between the failures and the time it took for them to occur. This analysis makes use of a two-parameter Weibull reliability distribution to output the probability the product will fail with time. The Weibull distribution treats the data as a linear function and makes use of the line's slope and intercepts to alter shape and scale of the probability curve. The Weibull distribution was chosen for this application because it mathematically makes predictions regarding a product's life span by fitting a statistical distribution to failure data from a sample of failed products. This outputs a probability distribution capable of making life-expectancy estimates.

It should be noted, that the distribution is created using only a sample of failed products and does not take into account systems not reporting errors. This creates the possibility for data that is partially skewed towards having shorter life expectancies. However, the Weibull analysis is intended for use using only failure data and accounts for systems that have not failed. Based on the data gathered from consumer survey, only 15% of consumers experienced an inverter failure. This should be considered when interpreting the data presented in the section. It should be known that this analysis was not performed to draw conclusions regarding products, but rather to provide a potential method for quantifying the reliability of PV products which currently lack these metrics.

This analysis can be used to make predictions about when a product will fail. Figure 10 displays the first year life estimates from the Weibull analysis performed. This data displays the probability that the inverters will fail at a given time (in hours). This can be used for large warranty milestones, such as five and ten years, to determine the probability the product will still be functioning. Figure 11 displays the inverter's failure probability curve. This graph displays the distribution of inverter failure expectancies with respect to time, and can be used to make more informed assessments of product quality, and could be included within the assessment matrix to enhance ATA consultations. The graph below is representative of the data received from the survey, but it is important to note that the probability of early failure is heighted because the majority of systems are young, and only infant failures actually have

	Time (hours)	Failure Probability
	0	0%
	730	2%
	1460	4%
	2190	7%
	2920	9%
	3650	12%
	4380	14%
	5110	17%
	5840	19%
	6570	22%
	7300	24%
	8030	26%
YEAR 1	8760	29%

Figure 10: Reliability analysis data

the opportunity to present themselves. Additionally, the vast majority of systems has not failed, but cannot be included in this analysis as there is no specific time of failure. The probability of failure can be used to determine the value of product warranty based upon when the system is likely to fail.

In order to account for systems that have not yet failed, analysis can be performed that treats failure data as a proportion of the entire population at various system ages. The percentage of system failures due to specific component failure was calculated as a function of time. This provides a more accurate representation of the survey results as many have not yet suffered failure. This supplies more realistic results when determining the probability of component failure for populations with still-

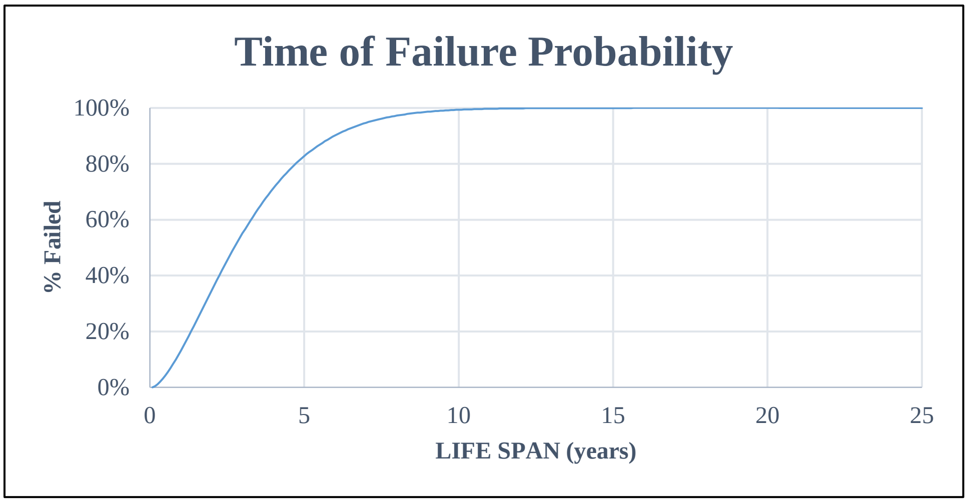

Figure 11: Inverter failure timing probability

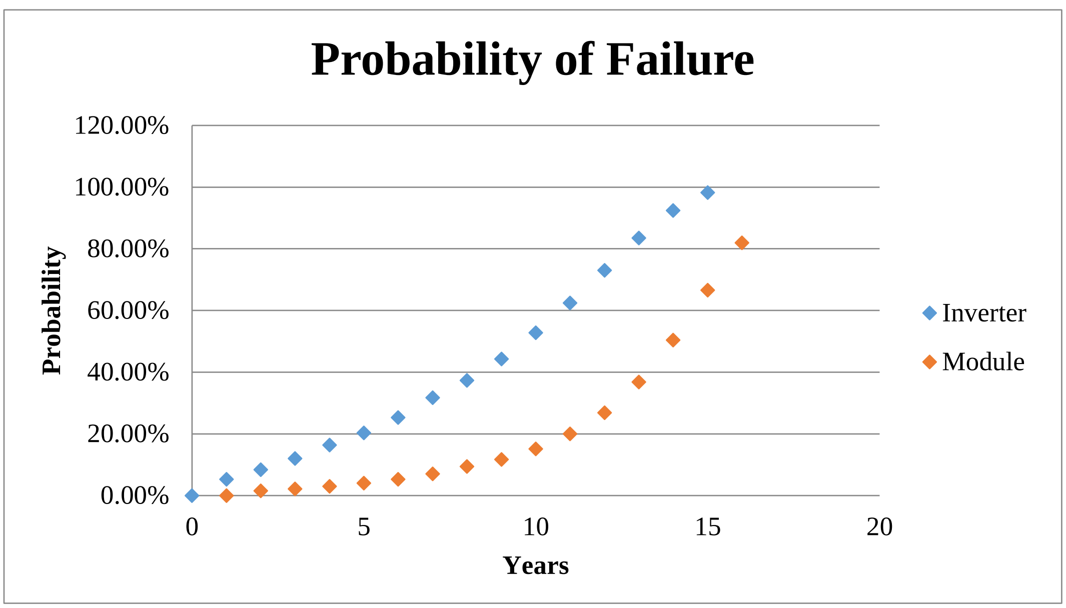

Figure 12: Probability of module and inverter failure

functioning components. Figure 12 displays the results of analysis performed on the survey data that can be used to estimate the probability of system failure with time. Notice that the probability of failure is significantly higher in inverters is significantly higher than modules, especially at young ages, which justifies longer warranties offered by module manufactures than those of inverters. The entirety of the analysis performed on present failure data can be found in an accompanying Microsoft Excel Spreadsheet.

3.3 Analysis of Consumer Experiences

The assessments provided by the ATA aim to provide consumers with the most optimal solar system for their needs. For this reason it is important to account for current consumer priorities when making these evaluations. In an attempt to better represent the needs of consumers when providing consultations regarding solar PV systems, a survey was distributed to Alternative Technology Association members. The data below is derived from a sample size of 868 survey responses using statistical analysis performed within Microsoft Excel. This section provides the results of this survey and analysis performed upon this data. The full results of this survey can be found in Appendix J.

Figure 13 displays the results of the survey provided to ATA subscribers regarding the most important factors when purchasing solar PV systems. Consumers were asked “What is most important to you when purchasing a photovoltaic system? (Please click and drag to rank)”. The results show that 70.62% of the consumers surveyed value the quality of their system above factors such as customer service, warranty, installer experience, and price when purchasing solar PV. The factor receiving the second highest amount of #1 rankings was Price, with only 9.75% of consumers ranking it first. This desire

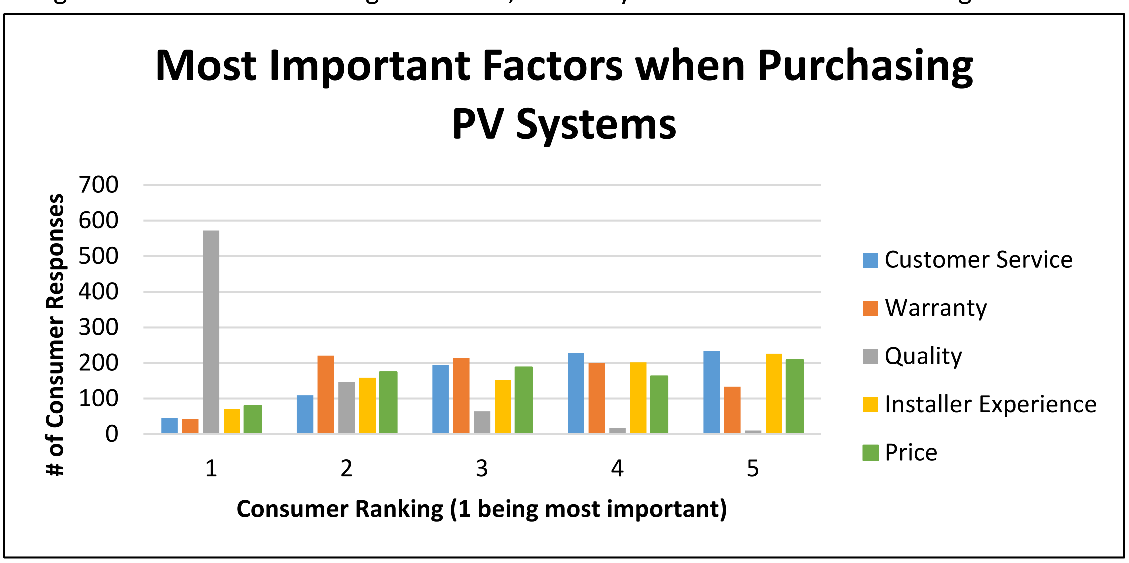

Figure 13: Survey results ranking the importance of various factors when purchasing solar PV

for high quality products displays the importance of a more comprehensive method for assessing the quality of solar PV components.

3.3.1 Analysis of Consumer Failures and Failure Timelines

Through the questions "How many times have you had an issue with your system?", "When did you first have an issue?", and "What was the cause of this issue?" the team was able to analyze common failure modes among consumers to gather real world data regarding system failures and expected timelines for these failures. Figure 14 depicts the number of consumer failures that occurred within specific timelines of owning a system. The slope of this curve represents the failure rate of systems over time. As the graph shows, the majority of failures occurred in the early stages of the system's life, with limited failures occurring beyond year eight. However, with the average lifespan of solar PV systems being 25 years, the failure rate is expected to increase again as time continues. This graph is a real-world representation of the MTBF "Bathtub Curve".

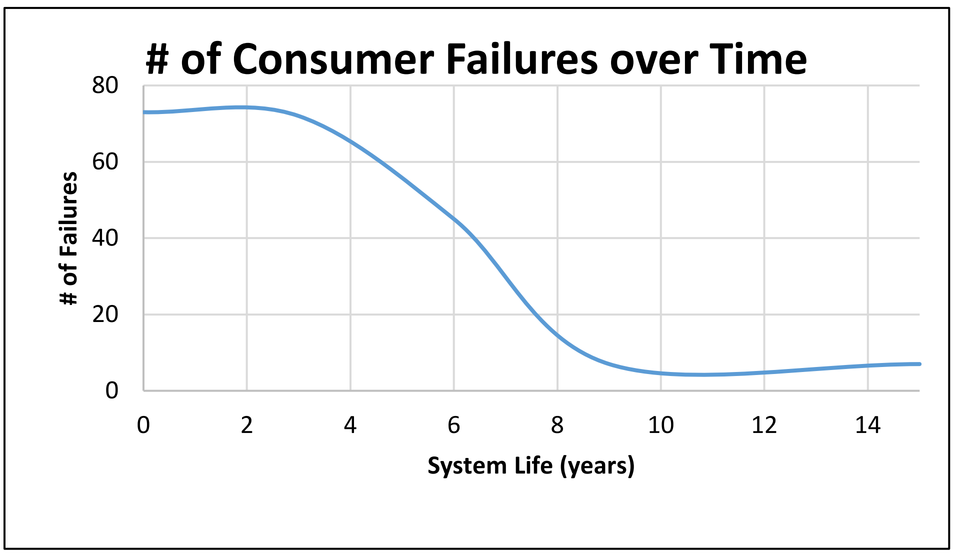

Figure 14: Consumer Failures over Time

As discussed in section 4.1.4, industry leaders were interviewed to determine common failure modes among systems. From our survey, real-world results regarding common failures among consumer systems was also gathered. Figure 15 depicts consumer system failure data for 205 consumers. As the pie chart shows, inverters were the most common system failure with 51% of consumers experiencing an inverter failure. The next most common was failures due to installation errors at 23%. This compares similarly to industry leader opinions regarding the most common failure. As the two most common failures were installation and inverter failures.

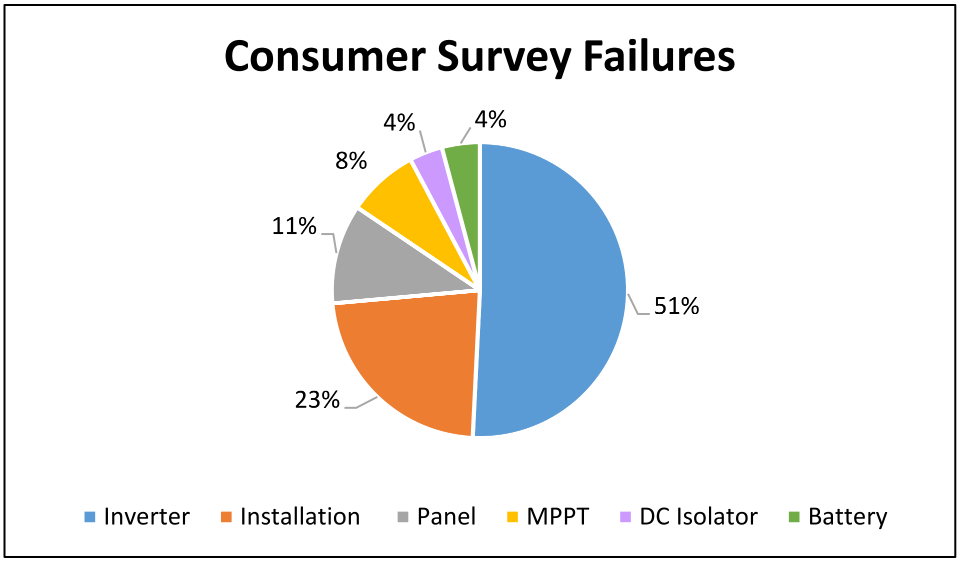

Figure 15: Consumer Failure Modes

3.3.2 Importance of Warranties

When consumers were asked to rank the most important factors when purchasing a solar photovoltaic system, warranty was most commonly ranked second behind quality. Warranties vary based upon the system component and type of failure. For example, inverter warranties typically range between 5 and 10 years, module product warranties are typically 10 years, module performance warranties are typically 20 to 25 years, and installation warranties are typically 5 years in length. When analyzing the most common failures as outlined above, inverters and installation errors were the most common failures, both which fall under warranties.

Inverters are the most common failure mode according to consumers at 51% of failures. Therefore, it is vital when purchasing a solar PV system to select an inverter with a good warranty. The team analyzed the survey data regarding inverter failures to evaluate how soon an inverter is likely to fail, as depicted in Figure 16. As the graphic shows, 74% of inverter failures occur within the first three years of installation. Therefore, the majority of failures that occur are covered within the warranty period. However, 26% of inverter failures occur some time after 3 years of owning a solar PV system. Therefore, ensuring good quality in the inverter and a longer warranty provides more coverage, should any issues arise.

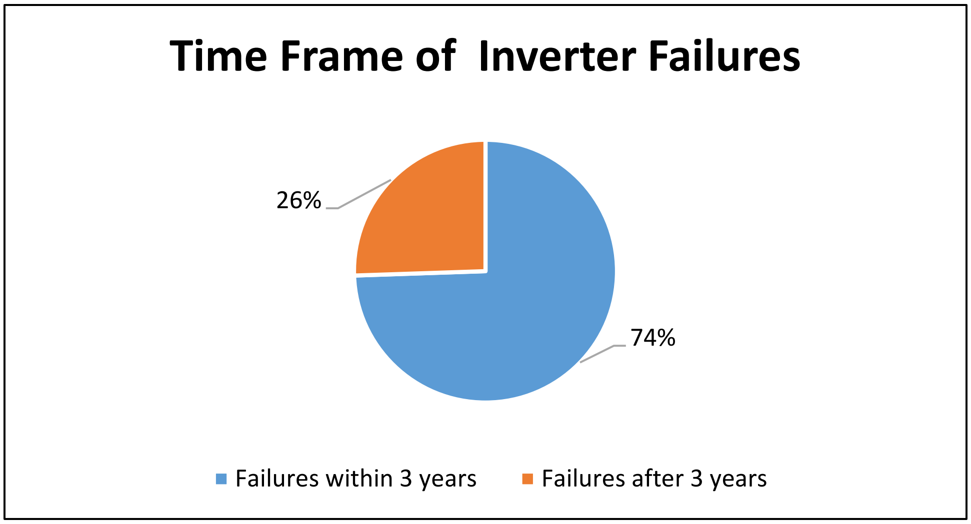

Figure 16: Timeframe of Inverter Failures

Installation failures were identified by industry leaders as the most common failure mode, and identified as the second most common failure mode by consumers. Installation warranties typically last 5 years and cover any issues in system performance as a result of poor installation. The team conducted a failure timeframe analysis, similar to that of inverter failures, for installation failures, as depicted in Figure 17. As shown below, an overwhelming majority, 91%, of failures due to installation errors occur within the first 3 years of the system's life. Almost all failures due to installation errors occur within the warranty period, however it is still important when selecting an installer to consider the reputation and experience of the installer so that these issues do not arise.

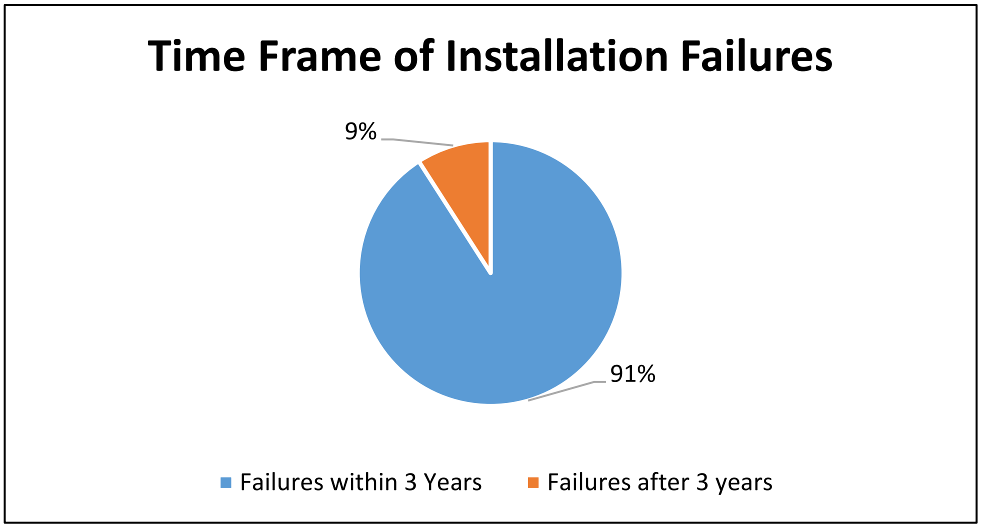

Figure 17: Timeframe of failures due to installation errors

3.4 Design of a More Comprehensive Assessment Matrix

3.4.1 Importance of Application Context within Matrix

The team has identified the need to tailor assessments more closely to individual applications. Therefore, the enhanced matrix will include a tab containing various factors pertinent to a given application, and adjust the matrix in accordance with client needs.

An important factor in the design of solar photovoltaic systems is the ratio between the capacities of the module array and its inverters. One common practice is to undersize the inverter in relation to the capacity of the array. This configuration can be ideal because panels hardly ever produce their nameplate power, and a smaller inverter is more efficient converting smaller levels of power. Though, analysis of DKAAS data suggests that if there is a high level of solar irradiance, inverters should not be overloaded beyond their rated capacity. This unnecessarily taxes the system, and the reduction in initial cost would be rendered insignificant after just 4 years of capped performance. However, applications that do not receive the same quantity of irradiance and/or are partially shaded should consider overloading the inverter because it is highly unlikely that the array will operate at its peak capacity and limit power for a significant period of time.

In addition to the sizing ratio, the application specific tab will include geographic location pertaining to the amount of solar irradiance a system would be subject to, potential panel shading, various cost restrictions, and system types (off-grid vs. on-grid) that will affect the factors determining the most optimal components. Based on the needs of the client these values will alter the weighting both of the tabs themselves and within each respective tab.

Another factor to analyze when creating a client specific matrix is energy consumption by time of day. Typically, in the southern hemisphere, panels installed with a north facing orientation generate the most electricity during the peak hours of the day (Energy Matters, 2017a). However, during peak sunlight hours in the middle of the day most people are at school or work and therefore not using their solar PV system. In an on-grid system, any unused power generated will be exported to the grid and in turn lost. Therefore, panel orientation should reflect peak hours of use for the consumer (Morris G., 2017). In most Australian households, this is a west facing orientation. Most households utilize most electricity in the evening hours, and west facing panel orientation generates electricity mostly during the evening hours when the sun is setting. This provides optimal coverage for the consumer, allows for less export to the grid, and more personal usage.

While this project focuses primarily on grid-connected systems, the application specific tab must provide considerations for both on and off grid applications. On-grid systems are solar PV systems that utilize solar energy to reduce usage and cost of on grid power for a homeowner. Off-grid systems are completely dependent upon solar energy for power, utilizing batteries to store excess energy and back-up generators in the case of a lack of energy generation. As mentioned previously, panel orientation is important to consider. In on-grid applications, west facing orientation is optimal to reflect peak hours of use. However, for off-grid applications, north facing orientation is optimal to collect the most electricity throughout the day for battery storage. Another major factor to consider for off-grid applications is customer service. If an issue should arise, it is important that the company responds quickly and provides assistance to the consumer's needs. (Morris, G. 2017) Without reliable customer service, off-grid systems could lose power and be without electricity for a long time as their system's problem goes unresolved.

3.4.2 Tabular Weighting Factors in Assessment Matrix

After assessing the current state of the Australian solar energy market and the Alternative Technology Association's assessment methodology, the study determined that customer priority was not appropriately taken into account in the previous assessment process. Therefore, the team conducted a survey to better gauge the current needs of Australian solar consumers. Making use of the mechanism established in Section 3.4, the consumer survey data was compiled and analyzed to create a more tailored tabular weighting mechanism.

$$Customer\ Service: (45 * 5) + (109 * 4) + (194 * 3) + (229 * 2) + (233 * 1) = \mathbf{1,934}$$

$$Warranty: (43 * 5) + (221 * 4) + (213 * 3) + (200 * 2) + (133 * 1) = \mathbf{2,271}$$

$$Quality: (572 * 5) + (147 * 4) + (64 * 3) + (17 * 2) + (10 * 1) = \mathbf{3,684}$$

$$Company\ Experience: (71 * 5) + (159 * 4) + (152 * 3) + (202 * 2) + (226 * 1) = \mathbf{2,077}$$

$$Price: (79 * 5) + (174 * 4) + (187 * 3) + (162 * 2) + (208 * 1) = \mathbf{2,184}$$

Figure 18: Tabular weighting calculations

This methodology for assigning weights and the accompanying data provides a more industry representative weighting mechanism. Previously, weights were established subjectively and had little quantitative data for justification. While the assessment was sufficient, it could use the supporting data to allow the ATA to better justify their recommendations. Table 3 displays the previous tabular weightings. The largest shift in weighting is the decrease in the importance of price. This shows that solar consumers are more concerned with purchasing a quality system that will operate consistently and efficiently for a long period of time, rather than minimizing initial cost. The importance of quality over cost was also emphasized through a questing asking if consumers would prefer to spend more on solar panels to guarantee they would not need repairs within the first 25 years. Approximately 50% of the respondents stated that they would be willing to spend more than 10% extra on a system of higher quality. In a similar fashion, the importance of both quality and warranty were increased to better represent this shift toward higher quality systems. These enhanced weightings display a trend towards higher quality systems and customer experience. Based upon the calculated scores, shown in Table 4, the enhanced tabular weighting percentages were established. These weights will be able to be shifted based on the given needs of an application, through the application specific tab, making the enhanced matrix even more representative of consumer and application needs.

Table 3: Previous matrix tabular weightings

	Customer Service	Warranty	Quality	Company Experience	Price
Weight	10%	25%	25%	10%	30%

Table 4: Enhanced matrix tabular weightings

	Customer Service	Warranty	Quality	Company Experience	Price
Score	1,934	2,271	3,684	2,077	2,184
Weight	15.9%	18.7%	30.3%	17.1%	18.0%

It should be noted that the survey was given to Alternative Technology Association members. These are members of the Australian community that are extremely passionate and knowledgeable about solar photovoltaic energy. This passion for solar power has the potential to skew the consumer data because not all Australians will be so well-informed regarding the importance of PV quality. However, their industry knowledge makes the ATA members an extremely useful source of information regarding solar PV. In addition, the application specific tab will have the capability to alter weighting based upon specific consumer needs. Therefore, the matrix will fully account for the necessary consumer groups.

3.4.3 Alterations to the Decision Matrix

The price section of the decision matrix has been altered to include columns for the size of the inverter as well as the module array. The previous assessment matrix recorded the power capacity as the smaller size of either the inverter or the array. This was restrictive as there are many situations where it is ideal to have inverter and array sizes that are not matched. The price per kilowatt will still be calculated as the overall indication of cost, but it will be dependent upon the size of the array as opposed to the smaller of the two. The matrix also has calculations tailored by the application specific tab to guarantee that the ratio in size between the inverter and array is within standards and not a sub-optimal configuration. This safeguard checks the capacity relationship between inverter and array against inverter maximum DC input and parameters set in the application tab. If the inverter size is found to be below the recommend limit, the system is flagged on the summary page.

The warranty section of the matrix has been altered to include the actual figures covered for each warranty. The warranty has been reorganized to display the information pertinent to the three major system warranties covering installation, the inverter, and panels. The matrix has also been updated with new equations to analyze both the years and coverage of each specific warranty. This eliminates the need to have a ranking key on the tab. All of the data is clearly displayed with the scores for each warranty. Each of the three types of warranties is all weighted to be equal and contribute a third to the entire warranty analysis. The panel warranty is unique because it is made up from two different warranties. Modules are covered by product warranties and performance warranties. The product warranty contributes more to the panel score (66%) than the performance warranty (33%) because the coverage is much stronger, replacing panels in the event of complete failure.

The quality section of the decision matrix includes information relating to reliability and performance of solar modules and inverters. This section of the matrix has been altered to separate quality into different categories consisting of performance and reliability. Both the specific panel and inverter are individually assessed when observing quality of the system. The metrics included for panel performance are efficiency, temperature coefficient, PTC value, and yield performance ration. The factors considered for panel reliability are junction box protection, glass type, and company reputation. Currently the values associated with each of these parameters has the same influence in the final score of panel quality. There were many more metrics assessed while building the decision matrix, but these key items were recognized as the most commonly discussed by industry leaders, the most widely available, and with the most distinguishable benefits amongst other panels. Assessment of inverter performance was characterized by efficiency, number of PPT inputs, and maximum DC inputs. Reliability was assessed within the matrix using protection class, presence of electrolytic capacitors, operating temperature range, and company reputation. These were all identified in interviews and research as crucial considerations when determining which type of inverter to purchase. The final score for the quality of each inverter and panel combination was determined by valuing each array and inverter at 50% each.

The installer experience tab within the matrix was altered to include columns considering installer accreditation and shipping practices of the company. Interviews with solar providers and manufacturers as well as failure data collected from the survey indicated that system failures can occur with poor installation, and that accreditation through the Clean Energy Council provides greater confidence that the installer is knowledgeable about proper procedures. Issues caused by faulty shipping were also identified as a common theme in interviews, and thus were included in the matrix. The tender document was revised to include shipping information, which can be directly imported to the matrix column. The experience tab was also adjusted to accommodate direct insertion of numerical values. The previous matrix relied upon a rating system to describe the amount of years and generation capacity installed by the company. The rating keys were eliminated and equations were developed to more easily enter, present, and accurately calculate information regarding installer experience.

Lastly, the customer service tab was changed to eliminate qualitative assessment. The Queenscliffe assessment had a customer service score assigned based off information included in a notes column. All companies received the same score, except for one which lacked specific information. In order to differentiate between companies and quantitatively assess customer service, the notes section was encoded and the common services were identified. Four major customer service offerings were found, and included as the new column headers. If the solar providers offered the specific services, then they received credit. Each of the four columns was equally weighted to contribute to the overall calculation of customer service.

3.4.4 Revised Matrix Comparative Analysis

A comparative analysis was conducted to determine how the new matrix performed in relation to the prior assessment methodology. The Queenscliffe consultation was used as the example case and the matrix was filled with information relating to the specific tenders and system components. The analysis was conducted similarly to the original bulk buy assessment. The new matrix had several alterations, mainly relating to additional metrics more indicative of system quality. Application parameters were completed with specific information characteristic of Queenscliffe to produce a more robust report.

The analysis was completed and final rankings of tenders were calculated and displayed within the matrix. The overall rankings had been significantly reordered from the original analysis conducted by the ATA in 2015. However, the top two offers as identified by the original decision matrix remained unchanged. These two offers were still identified as significantly better than the other systems. The only other offer that did not change in rank was the lowest ranked system because it was much worse than all the other tender requests. Table 5 below shows the rankings as determined by revised decision matrix and the rank change when compared to the original.

As indicated by Table 5, many photovoltaic system offers had major changes in rank. Both tenders submitted by City to Surf Solar Plus performed significantly better in the new matrix, and rose many positions. This is due, in part, to both offers delivering high quality products, albeit at a high cost. The new matrix placed greater emphasis on high quality systems while reducing the importance of price. Additionally, the new metrics and weightings introduced to the quality tab of the matrix reorganized the top systems, and identified City to Surf Solar Plus B as having the system of highest quality. Improved quality and installer experience scores caused it to rise seven spots. Radiant Energy Systems A and Massive Solar B both dropped in the rankings because their quality score decreased and they earned a lower customer service score because of the amount of services provided. The revised matrix relies more heavily on quantitative values indicative of quality and other factors, granting greater confidence in its decisions.

Table 5: Comparison of tender rank to prior methodology

Rank Change	Solar Provider	Percentage
--	Sustainable Solar Services B	78.2
--	Green Energy Options A	76.8
▲3	City to Surf Solar Plus A	74.7
▲1	Sustainable Solar Services A	73.5
▼2	Efficient Energy A	72.9
▲7	City to Surf Solar Plus B	71.7
▲4	Efficient Energy B	70.6
▲4	Green Energy Options B	69.7
▼5	Radiant Energy Systems A	68.3
▼3	Massive Solar A	68.2
▼1	Radiant Energy Systems B	66.0
▼3	Aus1Energis A	62.2
▼5	Massive Solar B	61.3
▲1	Aus1Energis B	58.5
▼1	New Generation Solar A	58.3
--	New Generation Solar B	57.2

4. Deliverables

Based upon our objectives, our team provided the ATA with five deliverables in addition to the final report. First, the team provided the ATA with a more comprehensive, enhanced decision-making matrix. Along with the decision-making matrix, an updated tender request document was provided to ensure the ATA receives all information needed when making an assessment. The team also provided the ATA with registries of both solar modules and solar inverters relevant to the Australian market. Accompanied with the team's reliability analysis example calculations, the team provided a survey for the ATA to use on their website to continuously gather reliability data. Lastly, the team provided the ATA with a 30 page summary of this report, providing a brief overview of the project and key findings.

5. Conclusions & Recommendations

Given the current state of the Australian energy market, solar photovoltaic systems have the potential to play a primary role in the country's energy generation. However, in order for this to happen it is necessary to optimize the balance between cost and quality to provide consumers with a cost-effective product that will function properly over time. This chapter provides recommendations to provide more comprehensive solar PV quality assessments and a concluding project summary.

5.1 Recommendations

Based upon the data and information collected through the methods described in the previous section, we have developed the following recommendations. These recommendations are directed towards the Alternative Technology Association and Australian consumers. In addition, this section includes recommendations for potential future projects.

5.1.1 Recommendations to Australian consumers

We recommend that consumers only hire installers that are accredited by the Clean Energy Council.

This study identified installation as one of the most common causes for failure with solar photovoltaic systems. Therefore to improve the reliability and performance of PV systems, it is critical that they are installed correctly. In an effort to mitigate the risk of these improper installations, we suggest consumers only make use of CEC accredited solar installers. To become a CEC accredited installer the company must have employees who fully complete required installation training courses, up-to-date electrical and working at heights licenses, and public liability insurance. In addition, companies are required to submit a case study of one of their installation to prove that they fully understand the proper techniques for installing solar PV systems. Companies must also re-apply for accreditation every two years and complete required training and professional development, which help to ensure installers are informed regarding the ever-changing Australian solar industry. This guarantees that a company that maintains CEC accreditation has been successfully installing products for an extended time period.

We recommend that consumers solicit post-installation inspections of their systems to ensure the quality of shipping and installation and perform regular maintenance on their systems.

While making use of CEC accredited installers will help to mitigate failures caused by installation errors, we recommend that consumers have inspections performed on their systems following installation. Consumers can solicit these inspections from their CEC accredited installer or from their state government. By conducting these inspections consumers will be able to determine the quality of the installation work. Using Maximum Power Point Tracking will allow the inspector to determine the initial functionality of the system compared to its manufacturer rating. This comparison makes it possible to identify any defects in installation, and correct them before they become more serious post-warranty problems. These inspections should be performed regularly following installation to ensure optimal system functionality.

In addition to regular inspections, consumers should be sure to perform the necessary maintenance required by the system. While it is important to purchase a high-quality system, it is equally important to properly maintain each component. This maintenance includes cleaning of the module glass, removing dust and dirt from the inverter, and ensuring the safety of all electrical connections. An accredited installer should be used for all maintenance, as these professionals have the ability and knowledge to perform the work safely. We also recommend that consumers keep a log of all inspections and maintenance done on the system to make potential warranty claims simpler when issues do arise.

We recommend that consumers purchase panels from a manufacturer that has conducted electroluminescence (EL) testing.

As mentioned earlier on in the report, electroluminescence testing conducted by a manufacturer can detect early microfractures and therefore ensure products leaving the factories are more likely to operate at a high level for a greater time period. This extra step in the manufacturing process can save panels from early microfractures and help ensure a healthy system life. Therefore, we recommend that consumers seek to purchase panels from a manufacturer that conducts EL testing on their products.

We recommend that consumers consider the following factors when purchasing solar photovoltaic systems and consult the ATA for further guidance.

When purchasing a solar photovoltaic system there are numerous things to consider, however this study has identified some critical factors affecting long-term performance and reliability. The first factor being the design of their system. There are a wide variety of design options for both modules and inverters, and purchasing the proper construction type for the given application is crucial to quality of the system. An additional design consideration when purchasing a system is the module/inverter sizing ratio. By oversizing the array to the inverter consumers can expect increased generation when the array is not operating at its maximum capacity, but will lose the excess power when the maximum is reached. For this reason, it is important for consumers to consider the amount of solar irradiance and shading their system will experience, the potential safety risk of overloading the inverter, and the potential financial benefits. However, it should be noted that consumers should never exceed the CEC specification of the inverter being rated to least 75% of the array's capacity.

In the case that a system does experience a failure, it crucial that the products purchased have proper warranties and that consumers understand the difference between the various warranties offered. Warranties offered for modules and inverters differ slightly in both coverage and length. Therefore, it is important to research the full extent of each warranty, which can be done by contacting the company directly or by consulting the ATA. Warranties are often representative product quality, and therefore a longer warranty is important in ensuring the quality of the system purchased and the installation. Although, warranty length alone should not be used to determine the quality of the warranty, and in turn the product.

A warranty is useless if a company is no longer in operation or does not have the capability of handling a warranty claim. Therefore, the location and reputation of companies should also be taken into account when purchasing solar PV systems. Through interviews with industry leaders, it was identified that when they are purchasing solar systems this is the most important factor influencing their decision. It is important that companies chosen by the consumer have offices located in Australia. This will make maintenance, warranty claims, and general customer service far easier. It also shows a commitment to providing the Australian people with a quality product. Failure to use a company with an Australian facility has the potential to lead to decreased long-term system quality due to lack of available support. Location also affects the reputation of the company. It is critical that consumers research online forums, investigate company information, and consult the ATA regarding the most reputable manufacturers, installers, and suppliers.

5.1.2 Recommendations to the Alternative Technology Association

We recommend that the ATA solicit consumer failure data and compile it into a running database of system errors.

This study identified the lack of available reliability data regarding solar photovoltaic products that are currently on the market. With the industry constantly changing, it is extremely difficult to produce valid product failure data and manufacturers are highly reluctant to provide this information to the public. For this reason, we recommend that that the ATA begin compiling information regarding the failures of its consumer's solar PV systems. This data will, with time, allow them to generate their own reliability data. We also recommend that they make use of the reliability calculation detailed in Section 4.2.5. Using this methodology provides the ATA with the probability that the project will still be operating properly after a given amount of time based upon the previously recorded failures. This analysis will allow the ATA to make comparisons and provide more informed consultations to their members in lieu of the unavailable published data. The team has completed a sample failure data survey for the use of ATA if they deem fit.

We recommend that the ATA solicit failure rate data from solar PV manufacturers.

In addition to gathering consumer failure data, we also recommend that the ATA request manufacturer failure data. Whether this data be from accelerated life testing or warranty claims, this data will increase the amount of reliability data available to the ATA and enhance the certainty to which they can make their assessments. The team was only successful in soliciting failure rate information from one solar manufacturer. If the ATA use their leverage to request this data it will greatly enhance their assessments. This failure data could also be included in their published buyer's guides for personal use by their subscribers, assuming the ATA does not need to sign a Nondisclosure Agreement to acquire the data.

We recommend that the ATA solicit technical information regarding the thickness of solar cells.

Through our research, we have discovered that the thickness of a solar cell makes the cell more or less susceptible to microfractures. Therefore, it is important to take solar cell thickness into consideration when providing consultations. However, this data is currently unavailable to the public. The team recommends that the ATA contact manufacturers to solicit information regarding solar cell thickness. In doing this, the ATA will be able to provide more knowledgeable consultations and reduce failures for consumers participating in these consultations.

We recommend that the ATA make use of the ENF Solar database when performing system assessments.

In our research of the most important factors and metrics used to determine solar system performance and reliability, we discovered the ENF Solar database. This database is operated and maintained by a private company who has staff members solely dedicated to ensuring the database is up to date and as comprehensive as possible. This has resulted in a constantly updating database with information regarding thousands of PV components and companies. We recommend that the ATA make use of the statistics available in this database when making consultations, updating their buyer's guides, and performing bulk-buy assessments. The website contains data regarding material composition, performance, test certifications, and third party test information. When this is combined with the analysis provided within this report, the ATA will be able to provide enhanced consultations to its clients.

We recommend that the ATA work in conjunction with the Clean Energy Council to develop industry guidelines regarding the shipping of solar PV system components.

Our study has discovered a major gap in the regulation of shipping solar PV system components. There are currently Australian regulations regarding both the manufacturing and installation of solar PV components, but there are no such regulations for shipping. Through our interviews and research it was identified that microfractures and other damages are often caused by poor shipping methods such as stacking panels or insufficient protective packaging. This is often because the shipping protocols are currently established by the manufacturers themselves. For this reason, we recommend that the ATA work with the Clean Energy Council to develop a set of guidelines for the proper transport solar PV components, especially solar modules. A set of guidelines similar to their current installation guidelines would increase the quality of the shipping process and reduce the presence of microfractures within solar modules. “CEC accredited installers” would be subject to similar training courses and reporting practices as installers, which would provide greater product quality assurance for an aspect that is currently overlooked.

5.1.3 Recommendations for future projects

We recommend a project be completed analyzing the quality of off-grid system components and expanding the ATA’s assessment methodology for these systems.

The current ATA assessment methodology is primarily focused on the evaluation of grid-connected photovoltaic systems. However, as the Australian energy market continues to change many consumers are making the switch to off-grid and hybrid systems. These systems require additional technology such as batteries and charge controllers. As these two system types become prevalent within the Australian market it will be crucial for the Alternative Technology Association to have the capacity to provide justifiable recommendations to its members regarding these technologies.

We recommend a project be completed to develop an educational program providing the public with the knowledge necessary to make informed solar photovoltaic system purchases.

This study has identified numerous factors affecting solar PV system quality and has provided the ATA with this information for use within their own assessments and consultations. However, it is highly important that the public is properly informed because they will actually be implementing these systems on their properties. We recommend a project be completed to develop an educational plan and program that can be presented to ATA members and the general public to increase their knowledge regarding the quality of the solar PV systems they are purchasing. Given the ATA’s experience with creating educational publications and holding these types of workshops, this project has the potential to greatly improve the Australian solar community.

5.2 Conclusion

As solar photovoltaic systems become more frequently used in Australia, the overall quality of these system has come into question. The purpose of this project was to develop a methodology to better assess the quality of these systems. This was accomplish by conducting interviews with industry leaders, surveying consumer priorities, and independent research.

Suppliers, installers, and manufacturers of solar photovoltaics systems were interviewed to determine what factors are most important when assessing the quality of PV systems. This was done in conjunction with interviews of key Alternative Technology Association employees. The factors that were identified include: the design of PV systems, the sizing ratio between modules and inverters, installation and shipping, and company reputation. In addition to the information gathered from interviews, surveys were conducted to take consumer priority into account when assessing what truly makes a quality PV system. Through this survey the team was able to establish that quality is the most important factor when purchasing solar PV systems and gather data regarding the failure of systems that have been used in the field for an extended period of time. This data could be used to calculate the probability of product failure and other reliability metrics. Lastly, independent research was performed to identify metrics capable of quantifying the long-term performance and reliability of these systems. The resulted in recommendations and a methodology for creating reliability data for solar PV products.

In order to make full use of the information collected, the project provided several deliverables for use by the ATA. These deliverables include: module and inverter product registries, a more comprehensive quality assessment methodology, a concise report detailing our findings, and recommendations for further improving the assessment of quality within PV systems. The product registries build upon the ATA's previously established buyer's guides and compile important quality information for the most common products on the Australian market. The assessment methodology was worked into a decision-making matrix that will allow for the comparison of various tenders for large scale applications. Lastly, the concise report and recommendations provide direction for furthering the research conducted by this study and how to best assess the quality of solar photovoltaic systems.

The work performed by the project team and the final deliverables provided to the Alternative Technology Association have great potential to affect the Australian solar industry. Up until this point the industry lacked a methodology for assessing the quality of solar photovoltaic systems. This project provides both a methodology and instructions to make further improvements. The implementation of this methodology will inform the Australian public of what factors have the greatest impact on the quality of their solar PV system. This will eventually lead to a market consisting solely of high quality solar PV systems that operate properly for the long-term. Given the current lack of energy security on the Australian market, consumers operating reliable, high-performance solar photovoltaic systems will be able to be confident that their energy will remain consistent, cost-effective, and capable of supporting the lifestyle all Australians are deserving of.

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